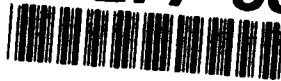


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December 1993

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ATOMIC FORCE MICROSCOPY

Joseph V. Beasock

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13. ABSTRACT (Maximum 200 words) Atomic Force Microscopy (AFM) has been used to study the surface microstructure of aluminum metallization. The effects of plasma cleaning and annealing on the surface structure of aluminum are shown and discussed. A brief description of the theories of Atomic Force Microscopy (AFM) and Scanning Tunneling Microscopy (STM) is given. The technique of AFM, the importance of tip geometry and sample orientation on image appearance and the significance of edge/tip interaction on interpretation of AFM data are discussed. Atomic level imaging capability of AFM is also demonstrated.					
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INTRODUCTION

Microcircuit reliability is dependent on the integrity of the metal interconnects that route the various power and signal currents throughout the device. A number of defects can seriously compromise the current carrying capacity of the metallization: including poor step coverage, areas of poor adhesion, void defects that cause narrowing, small grain size and nonuniform grain size.[1]. All of these defects adversely affect the electromigration resistance of the interconnects. In addition, the increasing densification of microelectronic devices demands smaller line widths which increases the electrical and mechanical stress on the metallization and causes accelerated line damage in the form of electromigration and stress voiding. Both of these processes are microstructure dependent.

Until recently characterization and analysis of the microstructure of microcircuit metallization was a difficult process. Most analytical techniques cannot achieve the required resolution or require severe preprocessing steps which in themselves may alter the microstructure that is being studied. As an example, scanning electron microscopy (SEM), which gives qualitative information of surface topography, requires a conductive coating of gold or graphite on nonconductive samples to minimize charging. Microcircuits are susceptible to damage from the high energy electron beam. In addition, SEM requires the sample to be placed in a vacuum. The output from SEM is two dimensional making it difficult to tell whether you are looking at a depression in the surface or a projection out of the surface.

Scanning tunneling microscopy (STM) and, recently developed, atomic force microscopy (AFM) are capable of collecting surface structure information on materials in their native state, nondestructively and with high relative and absolute resolution. AFM/STM data is, also, 3-dimensional and quantitative.

THEORY

Atomic Force Microscopy

Atomic force microscopy is a surface analysis technique based on the interaction force of a microscopic probe in contact with the surface under investigation. Images of the sample's surface topography are generated from the force variation as the probe moves over the surface. Two types of probes are available for AFM (see Figure 1), the standard probe and the enhanced probe. The standard probe (Figure 1a) consists of a pyramidal shaped structure. The tip of the pyramid approaches monatomic dimensions, but this probe has a low aspect ratio. As a result, the standard probe performs best on smooth flat surfaces.

The enhanced probe tip (Figure 1b) is formed by depositing a long needle-like structure at the tip of the standard probe. This needle-like deposit has a smaller lateral dimension and can resolve rougher surface structure than the standard probe. The result is an image that shows more detail and more accurately represents the actual surface

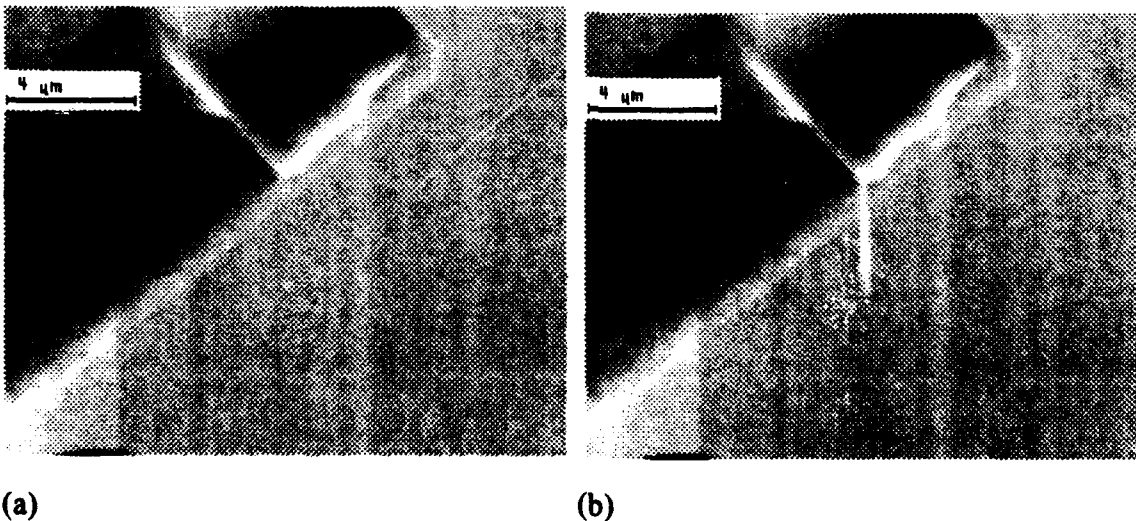


Figure 1. (a) Standard AFM probe. (b) Enhanced AFM probe.

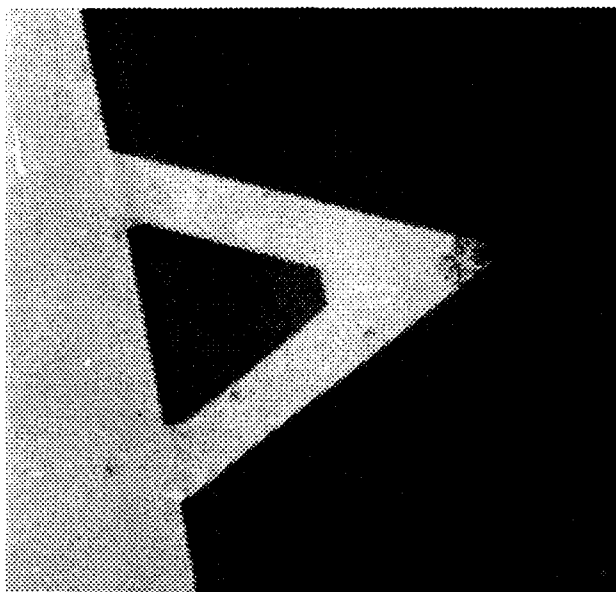


Figure 2. Illustration of triangular cantilever used for AFM. The black spot at the apex of the cantilever is the probe tip.

structure. The standard probe is best for atomic resolution, because the enhanced probe has a tendency to bend during scanning.

Probes tips are located at the end of a small cantilever (Figure 2). The cantilever acts as a spring which bends to allow the probe to deflect away from surface corrugations that would otherwise result in tip destruction. The bending of the cantilever is also important in controlling and measuring the force applied by the tip to the surface. The force and displacement are related by Hooke's law:

$$F = -kx,$$

where k is the spring constant of the cantilever and x is the displacement of the tip from the equilibrium position. Typical cantilevers have a spring constant of 1-2 newtons/meter. Changes in probe position of a fraction of a nanometer are readily determined. This

corresponds to a change in the interaction force of less than one nanonewton. The absolute resolution in any direction is better than 0.1 Angstrom. However, the relative resolution is scanner and scan area dependent.

During image collection, the interaction force between the probe and the surface is either measured (constant position mode) or held constant (constant force mode). In either case, the output signal is a voltage generated by a focused laser beam reflected off the back side of the cantilever into a differential detector (Figure 3). The error signal is amplified to give an easily measured output signal that is proportional to the interaction force.

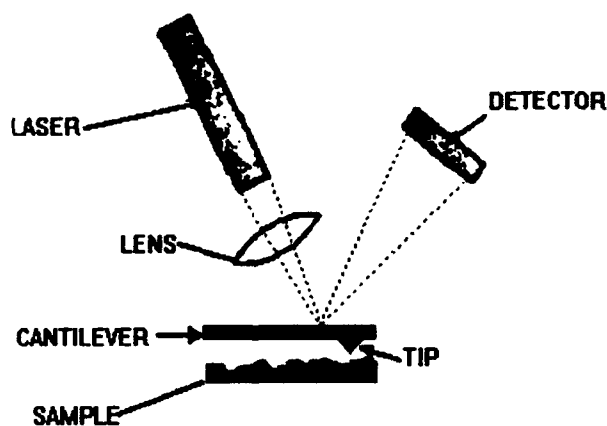


Figure 3. Detection of probe position using focused laser beam and differential photodetector.

Scanning Tunneling Microscope (STM)

Scanning tunneling microscopy is a noncontact scanning probe technique for surface imaging and analysis. As in AFM, the position of the probe can be accurately controlled in 3-dimensions with respect to the surface of the sample. The main difference

between STM and AFM is the method of controlling the probe position. In STM, the probe is usually an extremely sharp tungsten wire (ideally reduced to a single atom at the tip). When a potential difference is applied between the tip and the sample at sub-Angstrom separation, a current results due to tunneling of electrons across the region. The tunneling current is extremely sensitive to the separation distance of the tip and the sample surface. The sample is mounted at the end of a piezo ceramic tube which changes length when subjected to an electric field. The separation distance of the probe and sample is held constant using a high gain feedback circuit to generate an error signal which controls the voltage applied to the piezo ceramic transducer to maintain a constant tunneling current.

Data collection and the imaging process are similar in AFM and STM. The ultimate resolution of STM and AFM is also comparable (less than 0.1 angstrom). A disadvantage of STM not shared by AFM is that STM requires a conductive sample. Thus, STM analysis of nonconductive samples requires special processing that may hide or distort the surface structure. However, STM is better at atomic resolution imaging and illustrating atomic level defects. Although AFM can give atomic resolution images on ideal samples, there are no examples where atomic level defects have been imaged by AFM.

IMAGE PROCESSING AND ANALYSIS

During the imaging process, the probe is scanned over the sample in an xy plane. The scan is digitally controlled, thus each scan consist of a series of consecutive steps. The step size is scanner dependent, but user selectable. As the probe steps across the surface, changes in probe height (z - direction) result in changes in the output voltage.

The output voltage is read and recorded for each x,y location. This data corresponds to the surface topography, and is used to construct a topographical image of the surface.

Image analysis software is used to analyze surface features such as grain size, grain size distribution, step heights, metallization thickness, surface roughness, etc. Figure 4 illustrates a line profile of the surface of a metallization sample which gives quantitative information about feature sizes and heights. Line profiles can be generated in any direction.

Image processing techniques can also be applied to the data to construct and

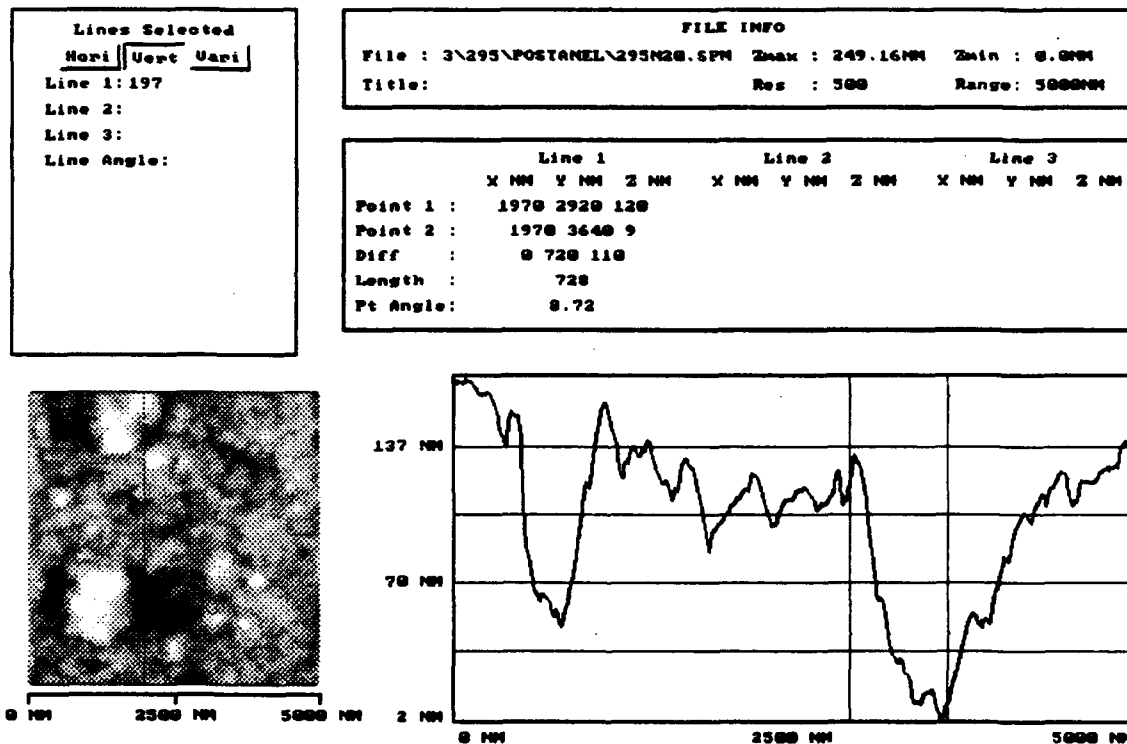


Figure 4. Line profile of 5µm x 5µm area of aluminum metallization.

display a variety of image formats. Figure 5 illustrates topography, shading and 3-dimensional image formats. Figure 6 illustrates a composite image generated from data collected in "step and scan" mode, which allows automatic data collection over an area much larger than the scanner's maximum range.

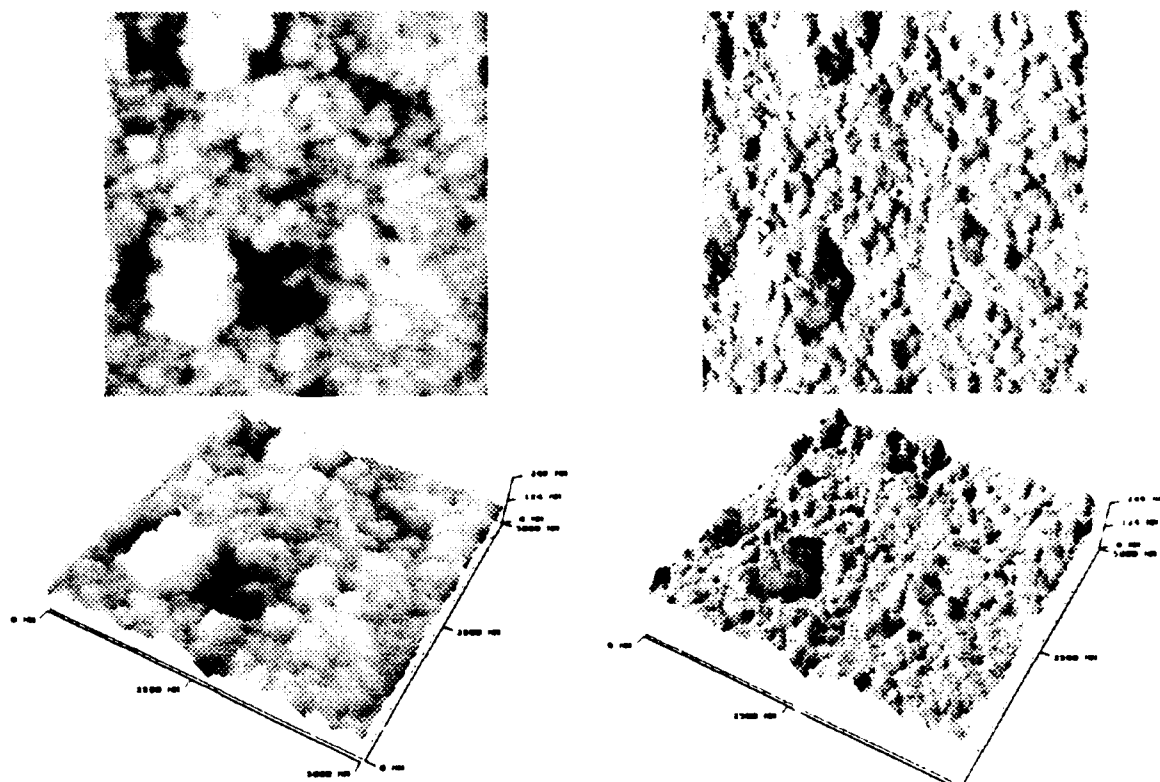


Figure 5. Topographical (left) and left shaded (right) images of aluminum bond pad on an electromigration test chip.

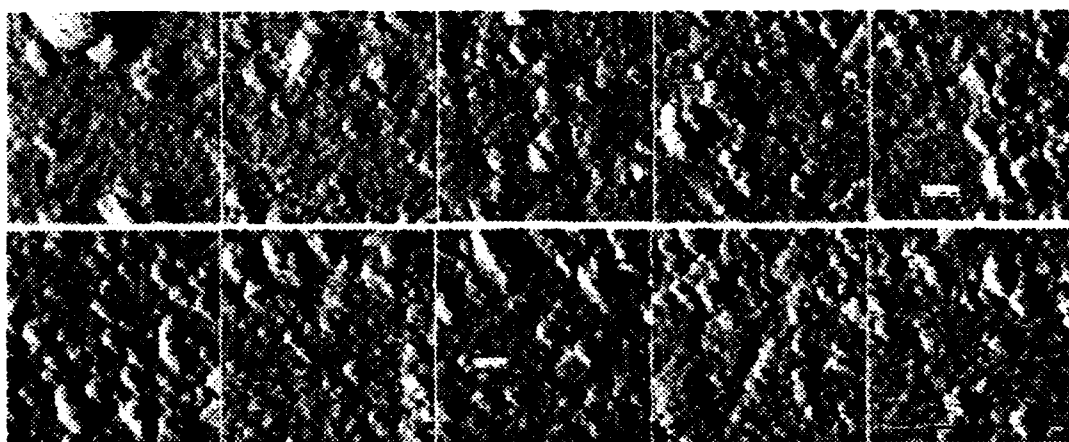


Figure 6. Composite image 25 μm x 10 μm .

SAMPLES

A graphite sample provided by TOPOMETRIX as a calibration standard was imaged to illustrate atomic resolution. This sample is normally used to determine whether a tip is suitable for atomic resolution and for dimensional comparisons at atomic resolution. All other samples were aluminum metallization test samples which were selected from a batch of electromigration test circuits generated from the work of LaCombe and Parks [2] in the early to mid 80's. These samples are being studied in an attempt to correlate the affects of microstructure on electromigration. Table I contains a description of the test circuit process conditions, and Figure 7 illustrates an electromigration test pattern that resides on the device.

TABLE I.
PROCESS CONDITIONS FOR TEST CIRCUIT

Metal Thickness (μm)	0.8
Oxide Thickness (μm)	0.4
Composition	Aluminum with 1% Silicon
Overcoat	SiO_2 (optional)
Overcoat Thickness (μm)	0.4
Metal Deposition	Sputtered
Anneal	1 Hour 400 C in Hydrogen

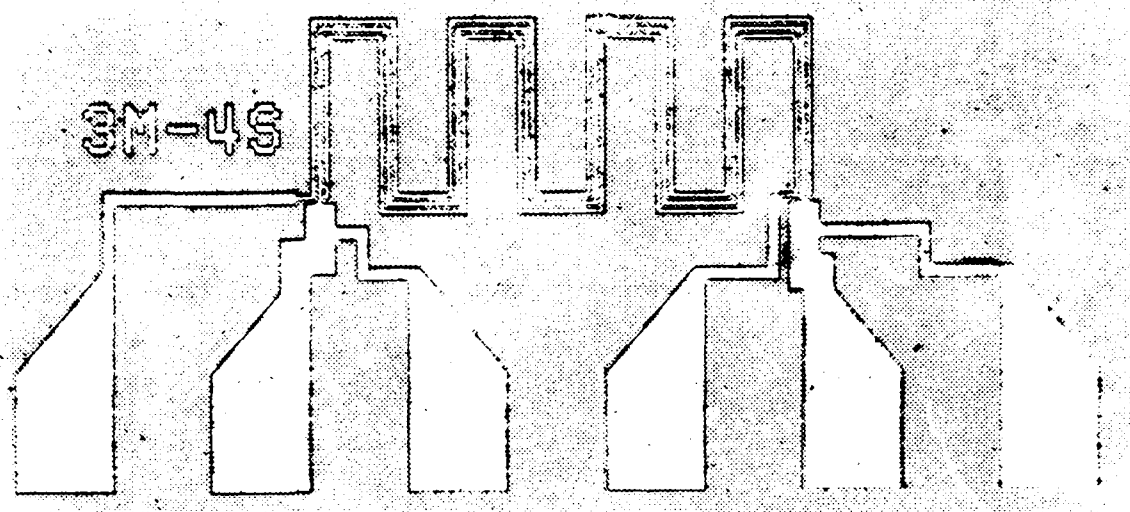


Figure 7. Meander stripe on electromigration test chip.

IV. EXPERIMENTAL

The electromigration samples contain aluminum metallization. Since aluminum has a nonconductive oxide layer, AFM was used in lieu of STM for analysis. The samples were imaged with a TOPOMETRIX TMX 2000 FORCE MICROSCOPE using a standard tip (spring constant ~ 1.5 N/m) operating in the constant force mode. Images were collected in air with an average force of ~ 1.5 nN. The image resolution is 500 points \times 500 points. The aluminum metallization samples were cleaned with methanol in an ultrasonic cleaner (10 min.) and rinsed with deionized water before imaging. Several samples were baked at 200°C for 500 to 1000 hours in a Blue M Model DL-1006A oven. Plasma etching was also done, on several samples, using a TEGAL Model "PLASMOD" plasma generator with CF_4 and O_2 .

V. DISCUSSION

The graphite sample required no special preparation or handling, it was simply mounted on a small metallic disk with a ground wire and placed on the scanning stage of the AFM. Mechanical vibration coupled through the bench top made it difficult to obtain a completely vibration free image, and several scans were required to obtain a reasonably noise free image. Figure 8 illustrates 2- and 3-dimensional imaging of this sample.

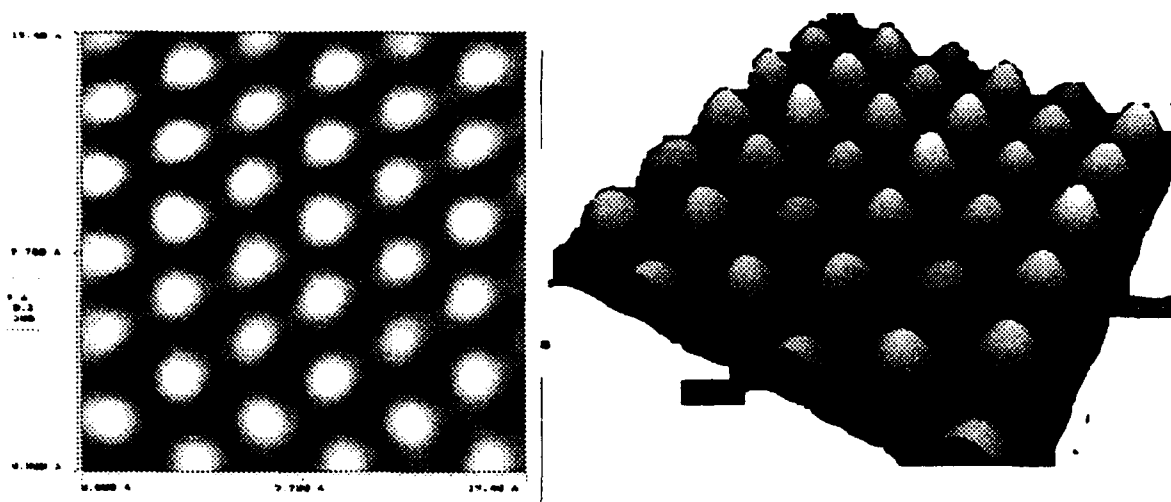
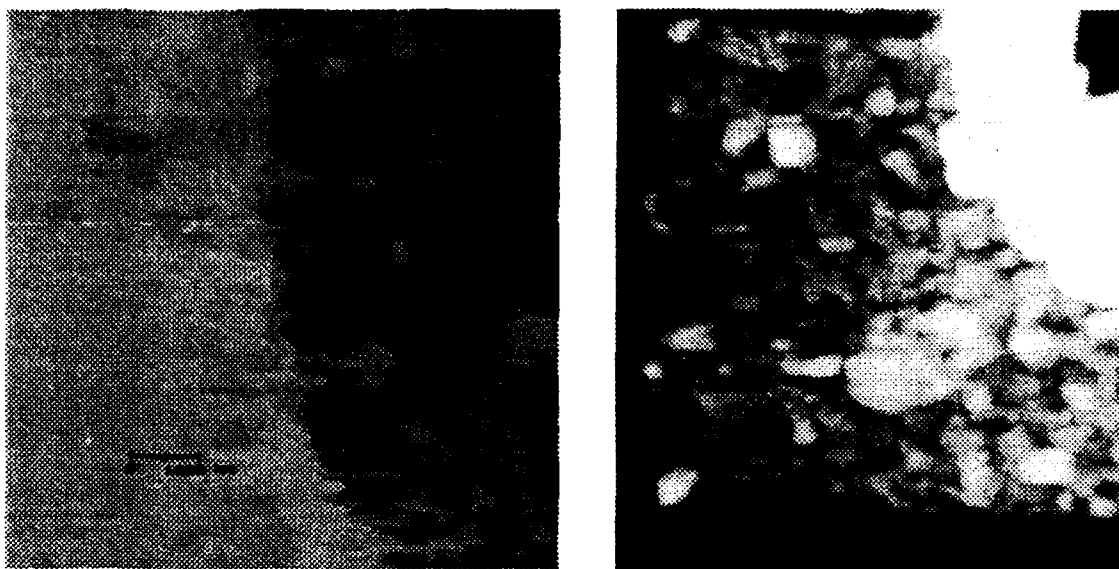


Figure 8. Topographical images of surface atomic structure of graphite.

The electromigration samples had accumulated varying amounts of surface contamination, since fabrication. Figure 9a illustrates the effect of this surface contamination on the image. Several methods of cleaning the samples, prior to imaging, were investigated, including plasma cleaning, rinsing with various solvents and ultrasonic cleaning. Ultrasonic cleaning with methanol followed by a deionized water rinse was found to give acceptable results. Ultrasonic cleaning with methanol for several minutes resulted in an extraordinary improvement in image quality as illustrated in Figure 9b.

There was a significant reduction in noise and considerable improvement in resolution of the surface microstructure.



a.)

b.)

Figure 9. Illustration of the effect of surface contamination on image quality. a.) Surface before cleaning. b.) Surface after cleaning with methanol followed by rinse with deionized water.

Figure 10 illustrates the effect of plasma etching. The sample came from a wafer that didn't have the overcoat applied. Carbon tetrafluoride (CF_4) with a small amount of oxygen was used in the etching process. Plasma etching was to be used for removing surface contamination and passivation. The area scanned was $3.1 \mu\text{m} \times 3.1 \mu\text{m}$. The etching process was interrupted at several intervals (30 sec., 5 min., 10 min. and 30 min.) to collect images. Images from three of the intervals were not useful. The 30 sec. etch showed little change in surface structure from the unetched condition. The 5 min. etch image was very noisy and the 30 min. etch image had a step height that put the area of interest outside the scanner's range in the z direction.

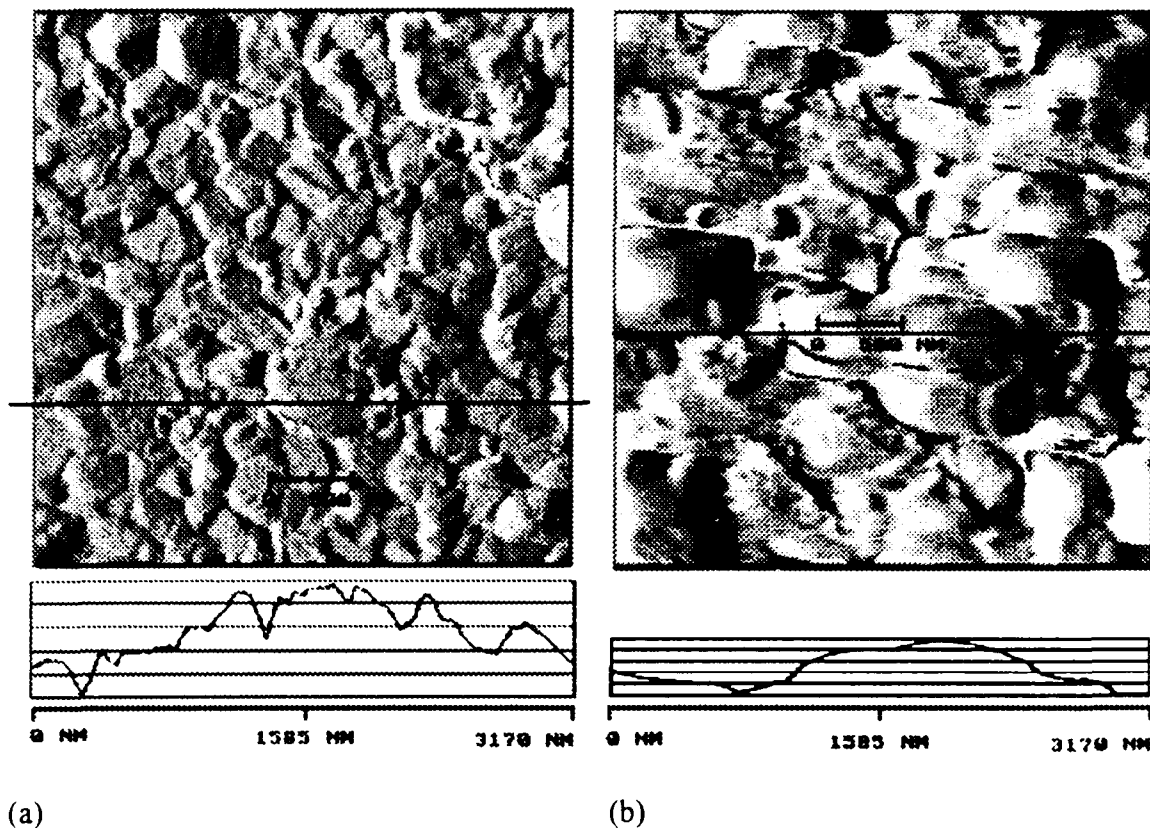


Figure 10. Plasma etched sample. (a) Surface structure before etch. (b) Surface structure after etch.

Figure 10a shows the surface condition before etching. Feature sizes are 0.5 micrometers or less. Figure 10b shows the surface after 10.5 minutes of etching. The line profiles shown below the images are indicative of the surface roughness. The two profiles were done in the same location and have the same vertical scale. The most notable difference between the two images is the change in roughness. The plasma etch had a leveling effect on the surface.

Clearly visible on the left of Fig 10b is a large feature approximately 1 to 1.5 micrometers across, the average grain size reported for this metallization. Recent measurements, however, gave grain sizes on the order of .3 to .5 μ m and it is questionable whether this is an individual grain. It appears that the feature in question could be made up of several smaller grains. The surrounding area is not as clearly defined, but also

appears to have features larger than the surface features before etching. Plasma etching will be investigated further, but at this time it does not appear to be useful as a nondestructive means of cleaning the aluminum surface or removing passivation.

Figure 11 illustrates the effect of low temperature (200°C) annealing on the surface morphology. The atmosphere in the anneal chamber was air. The images were collected at a bond pad on a device that had been passivated. The scan area was 9 μm on a side.

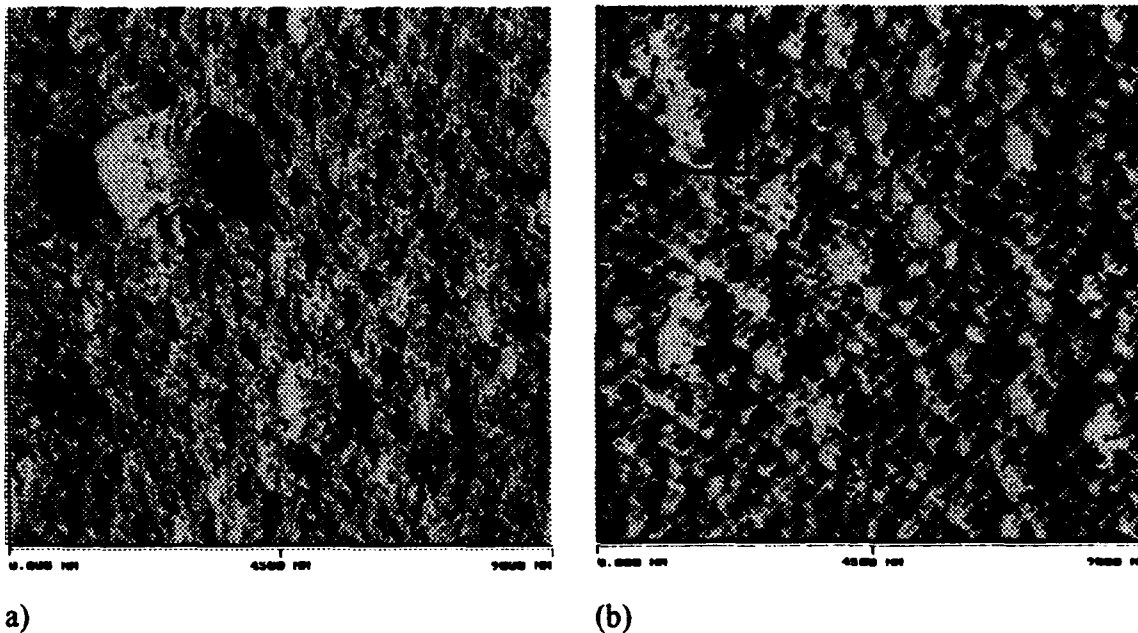


Figure 11. Annealed sample. (a) Surface structure before annealing. (b) Surface structure after annealing.

Figure 11a shows the surface of the metal before annealing. The microstructure in Figure 11a is much different from the previous sample, because this sample had glassivation applied and had seen additional processing steps. Figure 11b shows the surface after annealing for 125 hours. The two images are from approximately the same location on the sample. An exact correlation of features on the two images is not possible because of the dramatic change in surface features on the annealed surface. The majority of

surface features are less than 1 μm across in both images. Additional samples annealed for up to 500 hours at 175°C showed similar changes in surface structure. It is not clear whether the change in surface structure is due to annealing, surface restructuring or oxidation. Additional analytical techniques including depth profiles are being used to gain additional information about the chemical changes that occur.

Figure 12 shows an image of the annealed sample of Fig. 11, collected using the enhanced probe. The location of the area imaged is about the same as in Fig. 11. The boxed areas on the two images show the same feature. The improved detail of Fig. 12 is due to the higher aspect ratio of the tip. Tip geometry is an important consideration in not only interpretation of the images, but in the quality of the image as well. The finite size of the probe and its interaction with surface features often hides or distorts features on extremely rough surfaces. It is particularly important not to read too much information into an image of surface features with steep sloping side walls. The AFM can't obtain useful image information off a side wall if the slope exceeds the aspect ratio of the tip. The resulting image is simply the interaction between a random location on the probe and the top of the wall. This is better illustrated in Fig. 13 which shows the image formed when the standard tip goes over the edge of a metallization stripe. Research in the area of AFM tip geometry, characterization and artifacts is still in its infancy. Eventually, tip artifacts will become a minor annoyance in AFM data.

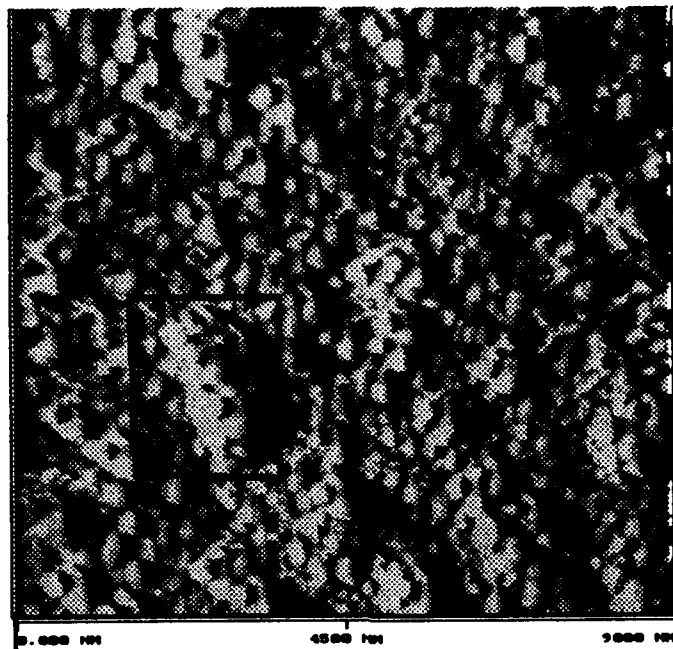


Fig. 12. Annealed sample image using enhanced probe.

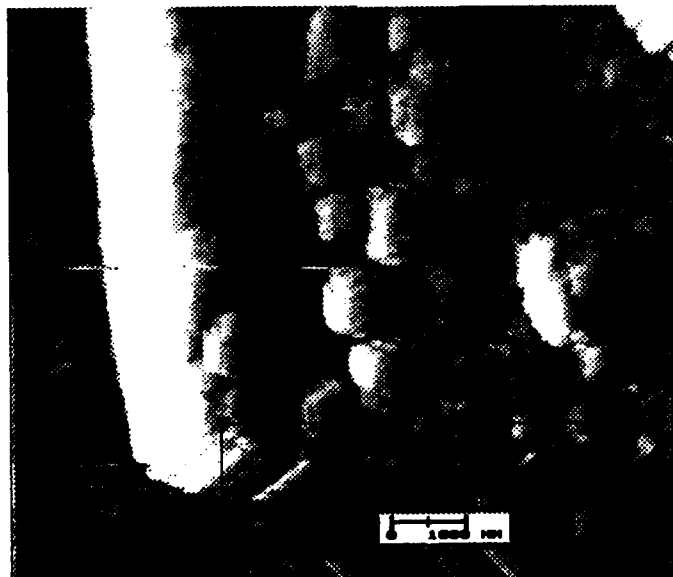


Fig. 13. Illustration of low aspect ratio probe on sample image.

CONCLUSIONS

AFM is a highly sensitive technique for the study of surface microstructure. Sample preparation is minimal and nondestructive. Surface data is quantitative, however, care must be exercised in interpretation of the data.

Analysis of low temperature (200°C) annealed aluminum metallization shows marked differences in the surface structure before and after annealing. The possibility of oxidation of the aluminum has been considered as a possible cause for this change and is being investigated. Aluminum forms a native oxide which is protective of the surface. This oxide grows to a thickness of about 40 Angstroms within a few seconds when freshly cleaned aluminum is exposed to air at room temperature. Typically, aluminum oxide thicknesses do not exceed 100 Angstroms [3]. However, recent data collected at Rome Laboratory [4] on aluminum metallization annealed for 500 hours at 175°C showed oxide thicknesses exceeding 100 angstroms. What effect this increase in oxide thickness has on the surface structure and electromigration is unknown at this time, but, for .25 μ m line widths the oxide could represent 10% or more of the cross sectional area. It is hoped that annealing studies presently in progress in high vacuum will provide some answers to the cause of the observed restructuring and its importance to electromigration.

The relation between the surface and bulk microstructure is also of considerable interest. Decreasing line widths give greater surface to volume ratios. At some point the surface physics become the predominant driving force in electromigration. Surface roughness will also have a more pronounced effect on electromigration of smaller geometry lines. AFM and STM will be crucial in obtaining quantitative relations between surface morphology and electromigration in small geometry devices.

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